

Postprint: Reliability Analysis of Ocean Current Permanent Magnet Generators Based on Permanent Magnet Temperature Field

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Abstract

Ocean current generators operate in marine environments that are considerably more severe than those of wind turbines, with challenges including seawater corrosion and sealing issues. Failure of an ocean current generator entails extremely difficult and costly hoisting and maintenance operations, making reliability analysis essential. This paper establishes a reliability model for the generator and employs the component stress analysis method for reliability prediction. Considering that permanent magnet failure is a unique fault mode of permanent magnet motors and that permanent magnets are susceptible to irreversible demagnetization at elevated temperatures, magnetic-thermal coupling simulation is conducted on the generator to analyze the influence of generator dimensional parameters on permanent magnet temperature and generator lifespan.

Full Text

Preamble

Reliability Analysis of Marine Current Power Permanent Magnet Generator Based on Temperature Field of the Permanent Magnet

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Abstract

Marine current power generators operate in underwater environments that are significantly more severe than those of wind turbines, with challenges including seawater corrosion and sealing issues. Once a marine current generator fails, lifting maintenance is extremely difficult and costly, making reliability analysis essential. This paper establishes a reliability model for the generator and employs component stress analysis for reliability prediction. Considering that permanent magnet failure is a unique fault mode of permanent magnet motors and that irreversible demagnetization readily occurs at high temperatures, magnetic-thermal coupling simulation is performed to analyze the influence of motor dimensional parameters on permanent magnet temperature and generator lifetime.

Keywords: Marine current power generator, reliability prediction, magnetic-thermal coupling simulation

1 Introduction

As a renewable energy source, ocean energy offers reliability, stability, and minimal environmental pollution, attracting increasing domestic and international attention. Marine current power generation resembles wind power generation but features higher energy density. However, marine current generators must address additional environmental challenges, including seawater corrosion, marine biofouling, sealing issues, and cavitation damage to blades. Given the extreme difficulty and high cost of maintenance when failures occur, reliability analysis is crucial for reducing failure rates during operation, minimizing expensive repair costs, and identifying approaches to extend service life.

Most marine current generators employ permanent magnet machines. Permanent magnet demagnetization represents a unique failure mode of such motors, and irreversible demagnetization readily occurs in high-temperature environments. The losses generated during electromechanical energy conversion ultimately convert to heat, causing motor temperature rise. Therefore, this paper conducts magnetic-thermal coupling simulation and examines how motor dimensional parameters (stator slot width, air gap length, and permanent magnet width) affect permanent magnet temperature and motor lifetime.

2 Reliability Modeling and Prediction for Marine Current Permanent Magnet Generators

Component stress analysis is simultaneously employed for reliability prediction. According to military standards, failure rate calculation formulas for windings and permanent magnets can be obtained as:

$$\lambda_{\text{winding}} = \lambda_b \pi_E \pi_Q \pi_K \pi_C$$

$$\lambda_{\text{PM}} = \lambda_b \pi_E \pi_Q$$

where λ_b is the basic failure rate (10 /h), π_E is the environmental coefficient, π_Q is the quality coefficient, π_K is the type coefficient, and π_C is the structural coefficient.

According to the NPRD (Non-electronic Parts Reliability Data) standard handbook, failure rates for certain mechanical components can be directly obtained: shaft failure rate $\lambda_{\text{axle}} = 7.8280 \times 10^{-6}/\text{h}$ and bearing failure rate $\lambda_{\text{bearing}} = 3.1114 \times 10^{-6}/\text{h}$.

Assuming each component's lifetime follows an exponential distribution, the motor reliability model describes the reliability/failure logic relationships between the system and its constituent units. This model enables quantitative allocation and prediction, helping identify design weaknesses for improvement. The selected structure for the marine current permanent magnet generator is a rotating pole type (permanent magnets on the rotor) with a radial magnetic circuit structure (permanent magnets directly facing the air gap, minimal leakage flux, and easy cooling of permanent magnets).

To establish the reliability model, all main functional units must be understood. According to GJB299C-2006 "Electronic Equipment Reliability Prediction Manual" and the U.S. Military Handbook "Electronic Reliability Design Handbook," component and assembly failure modes and their distribution ratios can be obtained, as shown in Table 1 .

Based on Table 1, the motor reliability model includes two sub-units: windings and bearings. Additionally, permanent magnet demagnetization is a non-negligible failure in permanent magnet motor reliability analysis, so the permanent magnet is also included as a unit in the model using series connection. The resulting motor reliability model is shown in Figure 1 [Figure 1: see original paper].

Assuming each component's lifetime follows an exponential distribution, the reliability after 1000 hours of operation is:

$$R_s(1000) = e^{-\lambda_s t} = e^{-\lambda_s \times 1000} \approx 0.9065$$

The Mean Time Between Failures (MTBF) of the motor is:

$$\text{MTBF} = \frac{1}{\lambda_s} = 10,190\text{h} \approx 1.2 \text{ years}$$

This indicates that after commissioning, the motor is predicted to experience failures after approximately 1.2 years. Therefore, preventive maintenance should be performed after the first year of operation to extend the random failure period and service life.

3 Failure Physics Analysis and Temperature Field Simulation of Permanent Magnets in Marine Current Generators

As a critical component in the motor reliability model, permanent magnets significantly affect motor reliability and service life. Since permanent magnet demagnetization is a unique failure mode of permanent magnet motors, focused failure analysis is necessary. To further analyze the failure mechanism, this paper approaches from the perspective of failure physics (also called reliability physics or physics of failure).

Failure physics is the science dedicated to studying product failure mechanisms, focusing on the root causes of failures through quantitative analysis and description of physical and chemical processes. Figure 2 [Figure 2: see original paper] summarizes the main failure mechanisms of permanent magnets.

This paper analyzes permanent magnet demagnetization from a temperature perspective. Due to the high temperature dependence of NdFeB performance, irreversible demagnetization readily occurs at elevated temperatures. Therefore, a temperature model for permanent magnets is established for temperature field simulation, with losses applied as input conditions. First, Maxwell software is used for motor loss simulation, with the obtained losses serving as heat sources for the temperature model. Then, Ansys Workbench software performs magnetic-thermal coupling simulation for the marine current permanent magnet generator, enabling the finite element model and thermal model to exchange loss and temperature values for dynamic demagnetization analysis.

The main technical specifications for the marine current generator are: rated power $P_N = 1$ MW; number of phases $m = 3$; rated voltage $U_N = 690$ V; rated speed $n = 12$ r/min. The main motor dimensions are: stator inner diameter $D_{i1} = 5.052$ m; stator effective length $L_{\text{eff}} = 0.6243$ m.

Loss simulation is performed first, including stator iron loss, copper loss, and permanent magnet eddy current loss. The simulation results are shown in Figure 3 [Figure 3: see original paper].

For temperature field simulation, convection heat transfer coefficients must be calculated. The coefficient between the stator end face and internal motor air is:

$$h_1 = 28 (1 + 0.25v)$$

The coefficient between the rotor end face and internal motor air is:

$$h_2 = 28 (1 + 0.45v)$$

where v is the kinematic viscosity of air.

Regarding the operating environment temperature for marine current generators, UK-based MCT Corporation has established monopile fixed support technology as the optimal choice. Considering installation barge and blade diameter requirements, typical sea depths range from 20-40 m. According to MCT's findings, seawater temperature at 20-40 m depth is approximately 15°C. Therefore, the ambient temperature for motor temperature field simulation is set to 15°C. The simulation results are shown in Figures 4 [Figure 4: see original paper] and 5 [Figure 5: see original paper].

The overall temperature contour reveals that windings have the highest temperature, dissipating heat sequentially to surrounding components. Since copper loss is the primary loss source, windings represent the hottest part of the motor.

In the temperature curve, the upper line represents maximum motor temperature and the lower line represents minimum temperature. The curve shows that temperature stabilizes at 500 s, reaching the maximum motor temperature. Since permanent magnet temperature will not exceed the maximum motor temperature, and the selected NdFeB permanent magnet's steady-state temperature is far below its Curie temperature, no irreversible demagnetization occurs, ensuring normal operation.

4 Influence of Motor Dimensional Parameters on Permanent Magnet Temperature

Excessive motor temperature causes permanent magnet demagnetization, making temperature monitoring essential during operation. This section investigates whether motor dimensional parameters (stator slot width, air gap length, and permanent magnet width) affect permanent magnet temperature through magnetic-thermal coupling simulation with 10%, 20%, and 30% increases in each parameter, identifying which parameter has the greatest impact.

4.1 Influence of Stator Slot Width on Permanent Magnet Temperature

Increasing stator slot width by 10%, 20%, and 30% yields the temperature contours shown in Figure 6 [Figure 6: see original paper]. The simulation data reveals that as slot width gradually increases, the maximum permanent magnet temperature also shows a rising trend.

4.2 Influence of Air Gap Length on Permanent Magnet Temperature

Increasing air gap length by 10%, 20%, and 30% produces the temperature contours shown in Figure 7 [Figure 7: see original paper]. The observed permanent magnet temperature shows a decreasing trend as air gap length increases.

4.3 Influence of Permanent Magnet Width on Permanent Magnet Temperature

This analysis considers 10% and 20% increases in permanent magnet width, as a 30% increase would exceed the pole pitch and dimensional limits. The results are shown in Figure 8 [Figure 8: see original paper]. Simulation data indicates that as permanent magnet width increases, temperature gradually decreases.

The temperature change rates for these three dimensional variations are calculated and compared in Figure 9 [Figure 9: see original paper]. The results show that air gap length variation produces the largest change rate, followed by slot width, then permanent magnet width. Therefore, air gap length has the greatest influence on permanent magnet temperature. During motor design, the impact of air gap length should be considered, preferably by increasing air gap length to reduce permanent magnet temperature and ensure reliable operation with extended service life.

5 Influence of Motor Dimensional Parameters on Marine Current Generator Lifetime

Since motor dimensional parameters affect motor and permanent magnet temperatures, and temperature significantly impacts motor lifetime, reliability analysis includes product lifetime estimation. For reliable motors, lower failure rates correspond to longer lifetimes. This section calculates motor lifetime under different dimensional parameters to observe their relationship.

Motor lifetime primarily depends on winding insulation lifetime, as temperature significantly affects insulation aging by accelerating physical and chemical reaction rates. An empirical formula summarizing the relationship between insulation lifetime and temperature is:

$$\ln T = -\frac{E_a}{R\theta} + G$$

where θ is insulation material temperature, $R = 8.317 \text{ J}/(\text{kg} \cdot ^\circ\text{C})$, and E_a , G are constants related to insulation material and chemical reactions. For Class B insulation motors: $G = 15.5$, $B = 10, 200$. Motor insulation lifetime can then be calculated based on different motor temperatures.

5.1 Influence of Stator Slot Width on Motor Lifetime

Based on previous temperature field simulations for 10%, 20%, and 30% changes in stator slot width, the resulting motor temperatures are substituted into equation (8) to calculate motor lifetime. The variation curve is shown in Figure 10 [Figure 10: see original paper]. As stator slot width increases, motor temperature rises and lifetime decreases, showing an inverse relationship.

5.2 Influence of Air Gap Length on Motor Lifetime

Using previously simulated temperatures for 10%, 20%, and 30% changes in air gap length, motor lifetime is calculated. The variation curve is shown in Figure 11 [Figure 11: see original paper]. As air gap length increases, motor temperature rises and lifetime decreases.

5.3 Influence of Permanent Magnet Width on Motor Lifetime

Based on previously simulated temperatures for 10% and 20% changes in permanent magnet width, motor lifetime is calculated. The variation curve is shown in Figure 12 [Figure 12: see original paper]. As permanent magnet width increases, motor temperature decreases and lifetime increases.

By observing motor lifetime through these three dimensional variations: (1) Motor temperature and lifetime are inversely proportional, highlighting the importance of temperature control for lifetime extension. (2) Increasing stator slot width and air gap length reduces motor lifetime, while increasing permanent magnet width extends lifetime. Therefore, to extend motor lifetime, stator slot width and air gap length should be reduced while permanent magnet width should be increased.

6 Conclusion

Considering that marine current generators are more prone to failure in underwater environments, this paper conducts reliability analysis primarily from the perspective of permanent magnet temperature field.

1. Reliability modeling and prediction are performed for the marine current generator, with Mean Time Between Failures calculated.

2. By varying stator slot width, air gap length, and permanent magnet width, magnetic-thermal coupling simulation reveals that increasing air gap length and permanent magnet width reduces permanent magnet temperature, while increasing slot width raises temperature, with air gap length having the greatest influence.
3. Motor lifetime under different dimensions is calculated and compared, showing an inverse relationship between temperature and lifetime. Increasing stator slot width and air gap length reduces lifetime, while increasing permanent magnet width extends lifetime.

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Note: Figure translations are in progress. See original paper for figures.

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